Search for Long-Lived Particles at CMS

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(On behalf of the CMS Collaboration)

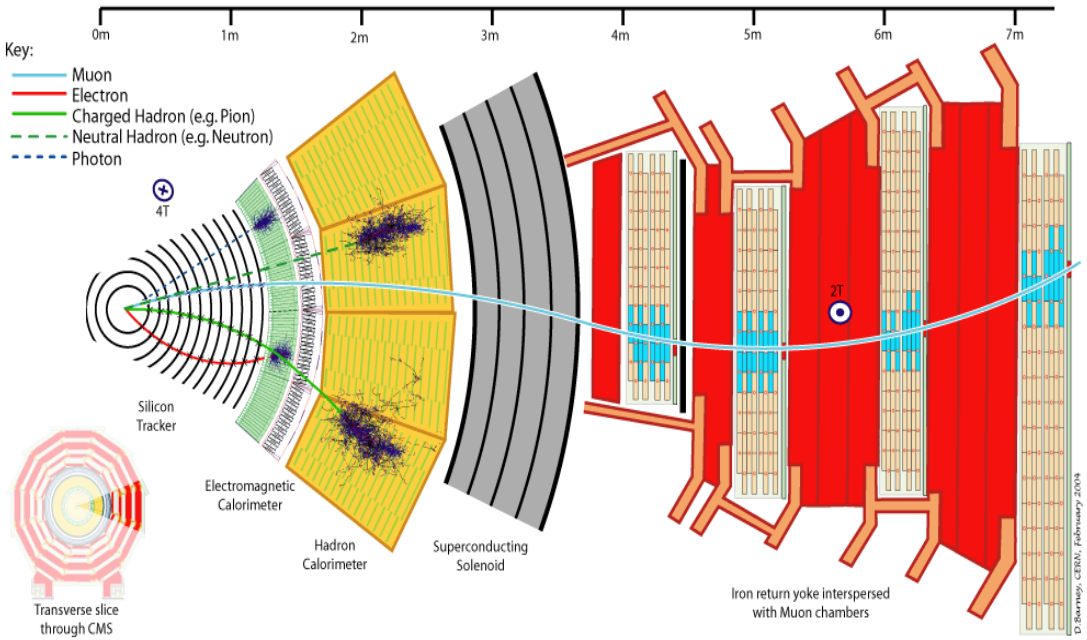
Supersymmetry 2011

28 August – 2 September

FNAL

Heavy Stable Charged Particles (HSCP)

- Predicted by many SM extensions
  - GUTS, hidden valley, ***split SUSY***…
  - Focus on production via strong interaction
  - gluinos and stops form **R-hadrons** ($\tilde{g}g$, $\tilde{g}q\bar{q}$, $\tilde{g}qqq$, $\tilde{t}q$, $\tilde{t}q\bar{q}$,etc.)
  - staus (mGMSB) produced directly or through gluino/stop decays



- Heavy
  - $m > 100\ GeV/c^2$
  - β<~0.9: large TOF
- Stable
  - Passes through muon system
  - Or decays in calorimeter!
- Charged
  - Large dE/dx
  - EM energy loss

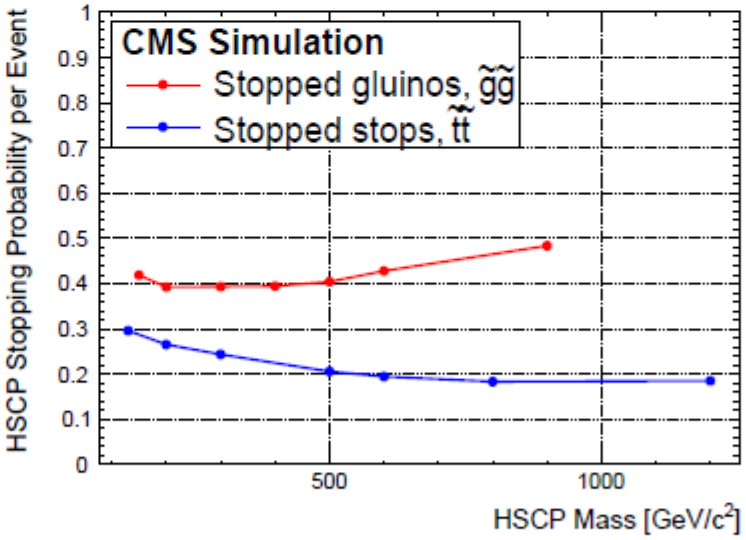
Simulating HSCP Production

- PYTHIA used for event generation
  - Various stop, gluino, stau masses
- GEANT4 simulates interactions of R-hadrons with CMS
- Various interaction models considered
  - charge suppression: R-hadrons with a gluino or bottom squark emerge as neutral particles
  - Gluino-> R-gluonball hadronization fraction *f*
    - $f = 0.1$, $f = 0.5$
  - “Cloud model” for R-hadron/matter interactions

Complementary Search Strategies

- "Direct Detection" of HSCPs
  - Search within 25-ns collision crossing (BX) or subsequent crossing (BX+1)
  - Large p_T, dE/dx in tracker
  - Long TOF as measured by muon system
    - In charge suppression scenario, neutral R-hadron doesn't interact with muon detectors

- "Stopped" HSCPs
  - β<~0.4
  - HSCP stops in hadron calorimeter (HCAL)
  - HSCP decay produces large HCAL deposit outside collision window



Direct HSCP Search

CMS PAS EXO-11-022

Detecting tracker-only Direct HSCPs

- dE/dX estimator:

$$I_h = \left(\frac{1}{N} \sum_{i=1}^{N} c_i^{-2} \right)^{-1/2}$$

  - *N=number of silicon hits*
  - *c_i= charge/length of i^{th} measurement*

- MIP estimator:

$$I_{as} = \frac{3}{N} \times \left(\frac{1}{12\,N} + \sum_{i=1}^{N} \left[P_i \times \left(P_i - \frac{2i-1}{2N} \right)^2 \right] \right)$$

  - *P_i = probability for MIP to produce charge <= i^{th} measurement*

Trigger: MET > 150 GeV

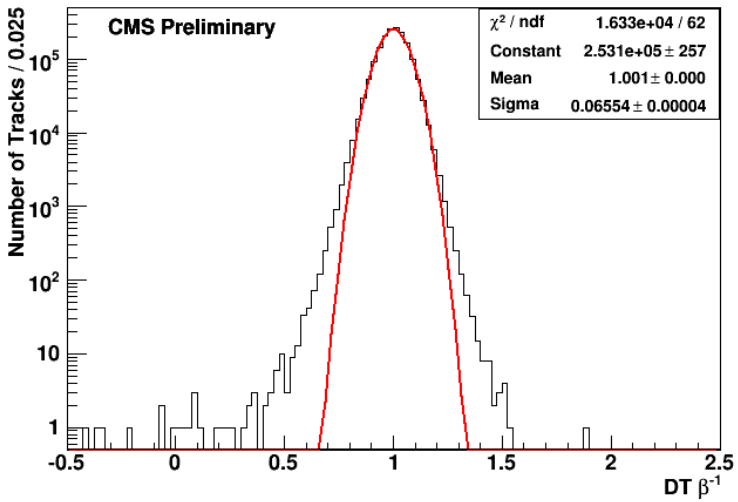
- MET calculated from PF jets (anti-k_T clustering)

Track selection:

- $|\eta^{INNER}|<1.5$; χ^2/d.o.f<5
- $p_T^{INNER} > 35$ GeV/c
- $\sigma(p_T^{INNER})/ p_T^{INNER} < 0.25$
- $d_z^2+d_{xy}^2 < 4$ cm^2
- Isolated:
  - $\Sigma p_T(0<\Delta R<0.3)<50$ GeV/c
  - $\Sigma E^{CAL}(\Delta R<0.3)/ p_T^{INNER} < 0.3$
- $I_h > 3$ MeV/cm

Detecting tracker+muon Direct HSCPs

- Require reconstructed muon matched to high-p_T track
  - Measure β from TOF: $1/\beta=1+c(\delta t)/L$
  - $1/\beta > 1$, $\sigma(1/\beta) < 0.07$



Trigger: muon p_T>30 GeV/c

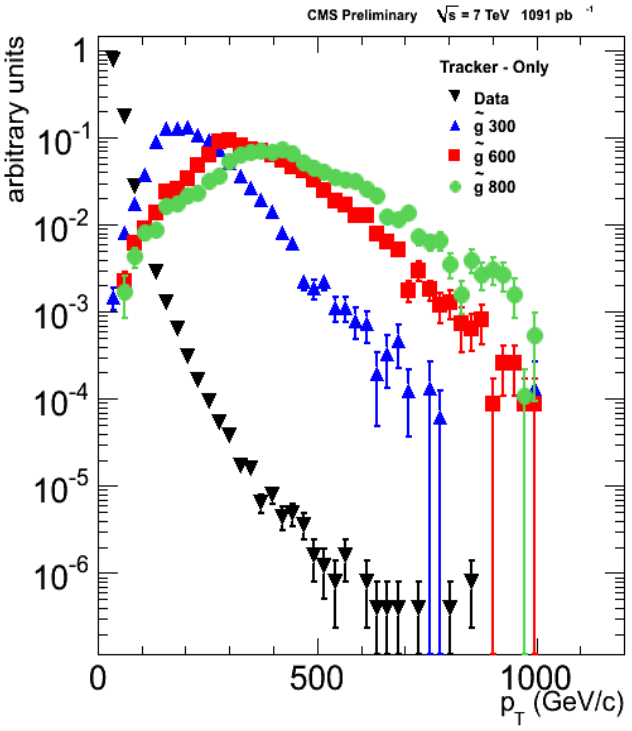
L1 trigger checks BX, BX+1

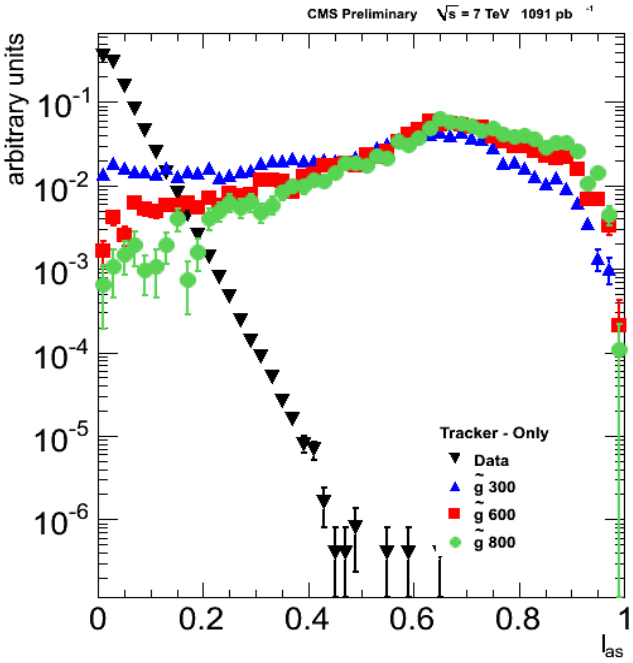
Track selection:

- Same as tracker only, but with loosened isolation cuts
  - $\Sigma p_T(0<\Delta R<0.3)<100$ GeV/c
  - $\Sigma E^{CAL}(\Delta R<0.3)/ p_T^{INNER} < 0.6$

Direct HSCPs: Search Strategy

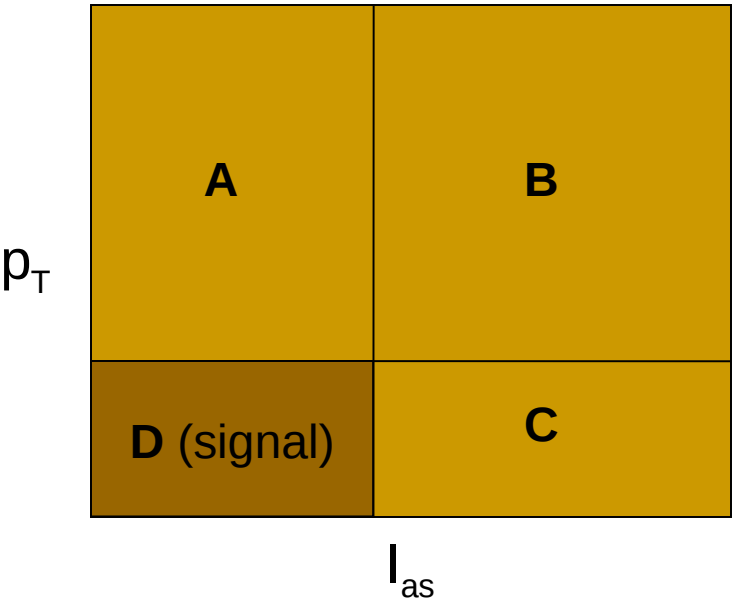
- Generate PYTHIA samples for various masses
  - $\tilde{t}$, $\tilde{g}$: 130-1100 GeV/c^2
  - $\tilde{\tau}$: 100-500 GeV/c^2
- Calculate measured mass for each track
  - **$I_h = Km^2/p^2 + C$**
  - Approximates Bethe-Bloch for $0.4 < \beta < 0.9$
  - K,C parameters taken from data
- Counting experiment for each HSCP mass
  - Choose p_T, I_{as} (and $1/\beta$) cut thresholds to minimize 95% CL upper limit

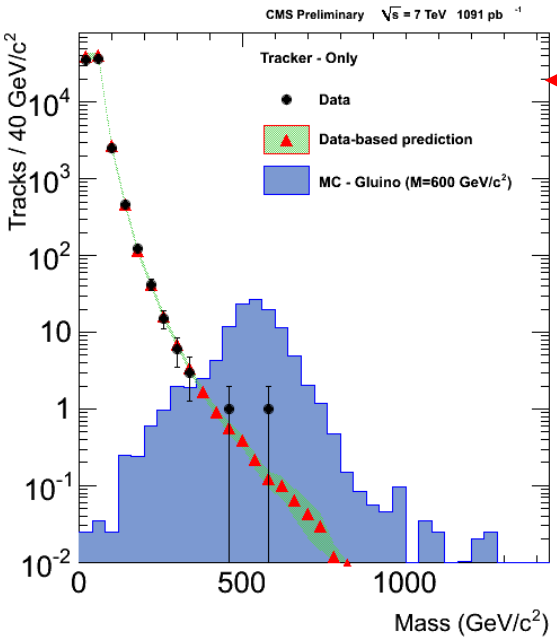




Direct HSCPs: Backgrounds

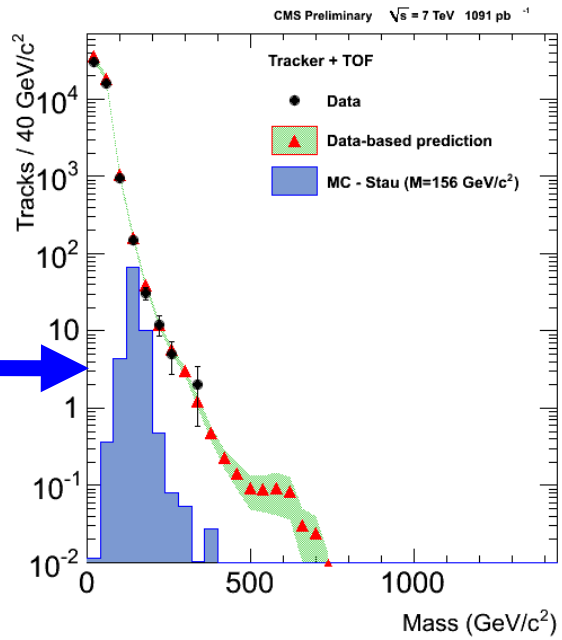
- Background from MIPs
- p_T, dE/dx measurements uncorrelated
- Estimate signal contamination from MIPs using p_T vs. I_{as} distribution
- For tracker+muon selection, use p_T, I_{as}, and $1/\beta$





"loose" tracker-only selection:
p_T>40 GeV/c
I_{as}>0.10

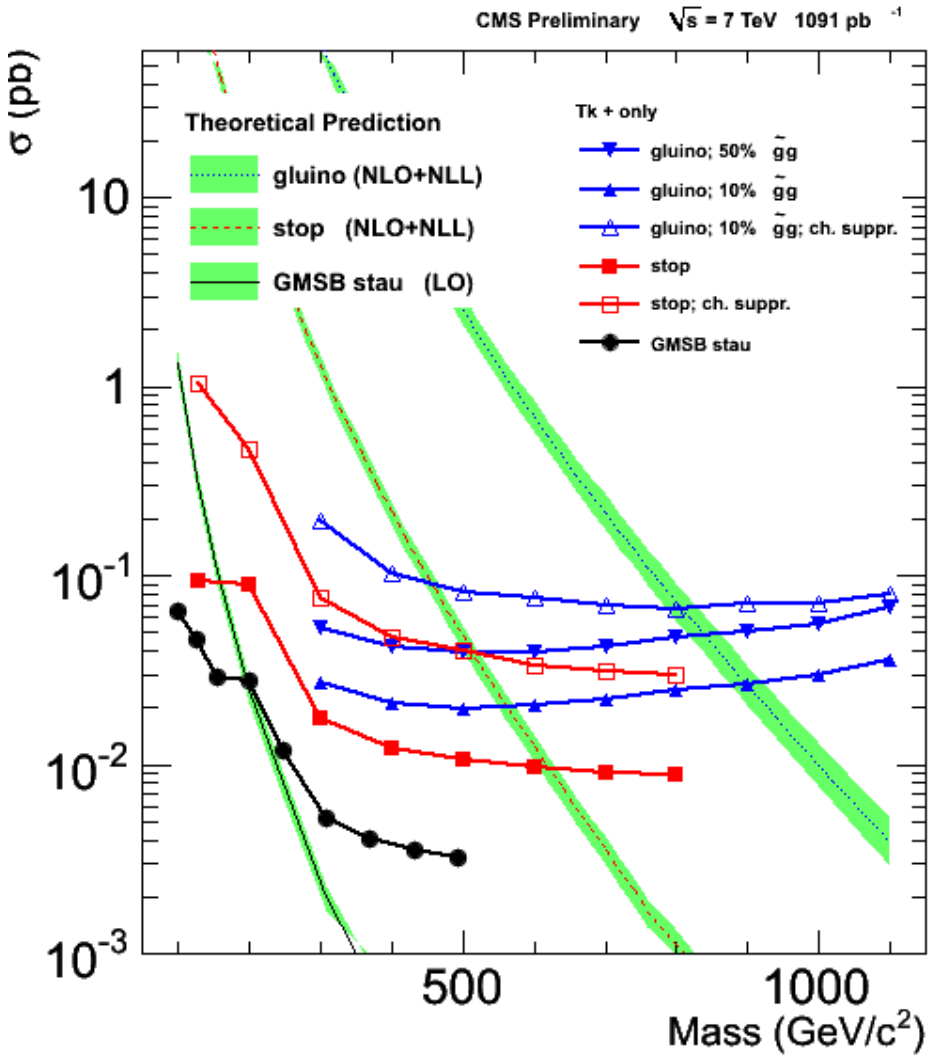
"loose" tracker+muon selection:
p_T>40 GeV/c
I_{as}>0.05
$1/\beta$>1.05



Direct HSCPs: tracker-only Results

- CMS PAS EXO-11-022
- 1.09 fb^{-1} of 2011 data
- No excess seen

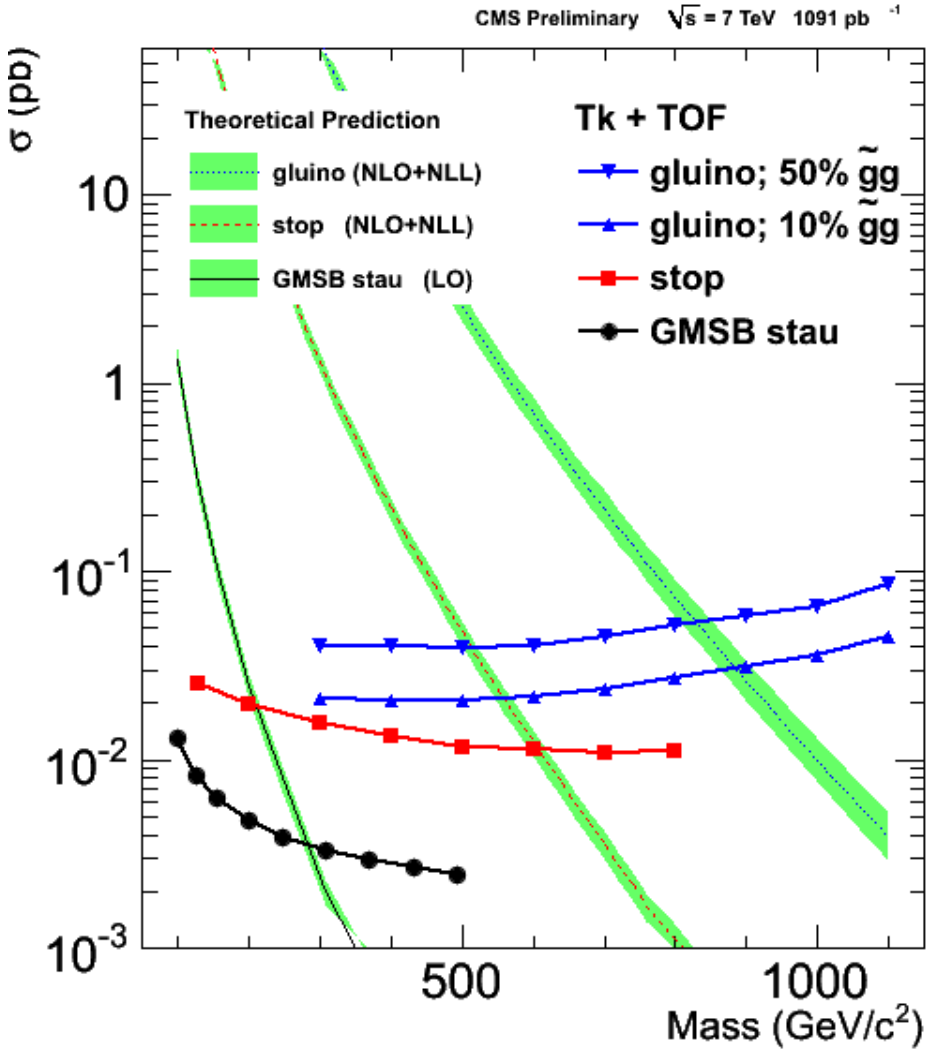
- ***Gluino mass limits:***
  - f = 0.1: 899 GeV/c^2
  - f = 0.1, charge suppression: 808 GeV/c^2
  - f = 0.5: 839 GeV/c^2
- ***Stop mass limits:***
  - f = 0.1: 620 GeV/c^2
  - f = 0.1, charge suppression: 515 GeV/c^2



Direct HSCPs: tracker+muon Results

- CMS PAS EXO-11-022
- 1.09 fb^{-1} of 2011 data
- No excess seen

- *Mass limits (f = 0.1):*
  - gluino: 885 GeV/c^2
  - stop: 829 GeV/c^2
  - stau: 293 GeV/c^2



Stopped HSCP Search

CMS PAS EXO-11-020

Triggering on Stopped HSCPs

Stopped HSCP decay signature:

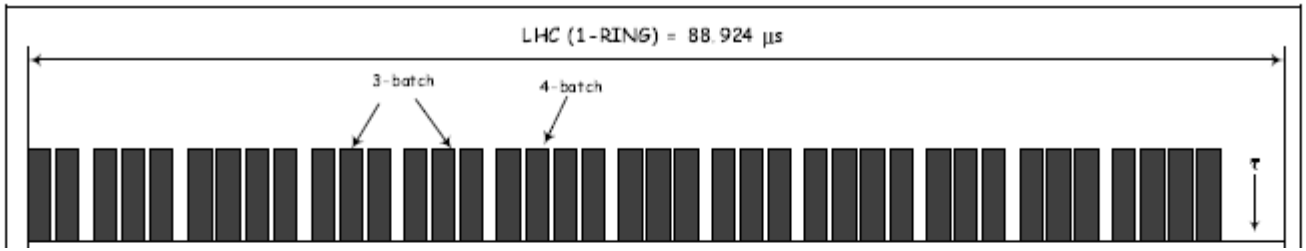
- large energy deposit in HCAL
- Not associated with halo
- Not (necessarily) in time with collisions
  - *Live time decreases as number of filled bunches increases*

Stopped HSCP trigger requirements:

- Jet E_T>50 GeV; $|\eta_{jet}|$<3.0
- Veto on beam halo (muon endcap) trigger within ± 1 BX
- Veto on BPTX trigger within ±1 BX

$N_{bunches}$	$N_{collision}$ (in CMS)	f_{live}
228	214	85%
336	322	78-79%
480	424	68%
624	598	61%
768	700	50-51%
912	874	44%
1092	1042	33%
1104	1042	32%
1236	1180	25%

Stopped HSCP: Simulation

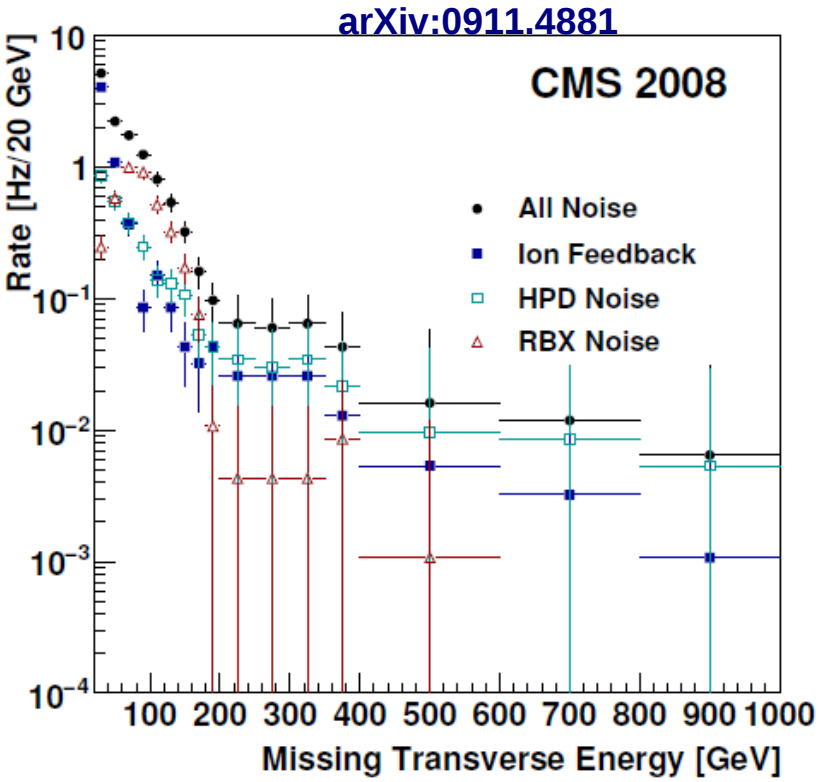


• 3564 bunches orbit
• 25 ns per bunch
• (up to) 2808 filled bunches

- HSCP decays do not need to occur within collision BX
- Toy MC used to produce distribution of decay times
  - Varies with HSCP lifetime, τ
  - Varies with LHC bunch structure for a given fill
- Produces “effective integrated luminosity” for a given τ

Stopped HSCP: HCAL Noise Background

- Sporadic noise observed in HCAL barrel and endcap
  - **Ion Feedback:** single HCAL channel
  - **HPD noise:** up to 18 channels in single ϕ slice
  - **RBX noise:** up to 72 channels, spanning 4 consecutive ϕ slices
    - **$\Delta\phi$ ~ 0.35, $\Delta\eta$ ~ 1.5**



Identify HCAL noise through geometry and pulse shapes of energy deposits

Stopped HSCP: Background estimation

Background sources:

HCAL Noise

Beam-related (Halo, beam-gas, …)

Cosmic Rays

Measure background rate from 2010 data

(Low instantaneous luminosity)

Stopped HSCP: Event Selection

Beam-Related Cuts
Veto if:
- **±2 BX from beam**
- **Vertex found**
- **Beam halo identified**

Selection Criteria	Background Rate (Hz)	Signal Efficiency %
trigger	21.5 ± 0.008	31.3
BX veto	8.61 ± 0.005	31.3
Vertex veto	8.61 ± 0.005	31.3
Halo veto	8.28 ± 0.0049	31.2
Cosmic veto	8.19 ± 0.0049	26.8
Noise veto	6.79 ± 0.0044	26.2
$E_{jet} > 70$ GeV	$2.63 \pm 0.028 \times 10^{-2}$	14.6
$n60_{jet} < 6$	$2.63 \pm 0.028 \times 10^{-2}$	14.5
$n90_{jet} > 3$	$2.33 \pm 0.082 \times 10^{-3}$	13.3
$nTowiPhi < 5$	$4.0 \pm 1.1 \times 10^{-5}$	13.3
$E_{iphi}/E_{jet} < 0.95$	$2.3 \pm 2.3 \times 10^{-5}$	13.3
$R_1 > 0.15$	$2.3 \pm 2.3 \times 10^{-5}$	13.4
$0.1 < R_2 < 0.8$	$2.3 \pm 2.3 \times 10^{-5}$	13.4
$0.3 < R_{peak} < 0.7$	$1.7 \pm 0.7 \times 10^{-5}$	13.3
$R_{outer} < 0.3$	$1.7 \pm 0.7 \times 10^{-5}$	13.3

- **Reject MIPs, jet energy fluctuations**
- **Also require $|\eta_{jet}|<1.0$**

Noise-Related Cuts

Background rates measured in 2010B dataset

- **Signal efficiency quoted for gluino mass = 500 GeV/c², neutralino mass = 400 GeV/c²**
- **Efficiency relative to events in which at least one gluino stops within CMS**

Stopped HSCP: Analyses

Counting Experiment

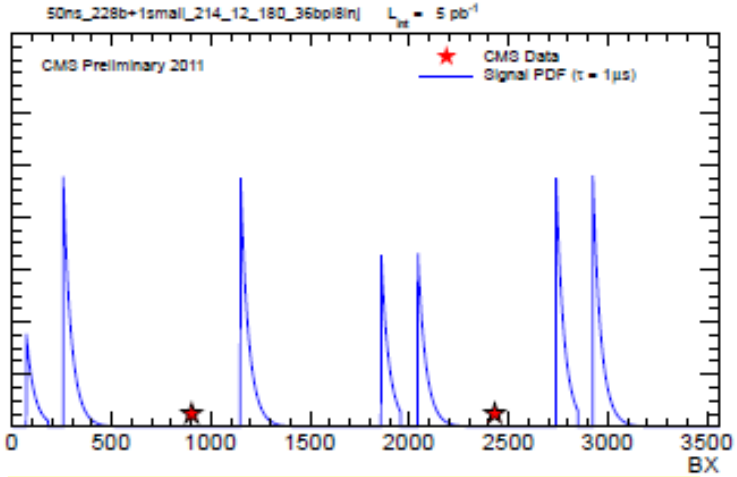
- Consider HSCP lifetimes τ from 75 ns – 10^6 s
- Count events in sensitive time window
- τ<89 μs: window=1.3τ
- Each event assumed to come from current fill

Lifetime	$L_{eff}(pb^{-1})$	Expected Bg	Observed
75 ns	4.3	0.11 ± 0.05	0
100 ns	12.5	0.35 ± 0.14	0
1 μs	139	3.3 ± 1.3	4
10 μs	352	10.1 ± 4.1	9
30 μs - 10^3 s	360	10.4 ± 4.2	10
10^4 s	268	10.4 ± 4.2	10
10^5 s	65	10.4 ± 4.2	10
10^6 s	7.5	10.4 ± 4.2	10

Observed events for various HSCP lifetimes

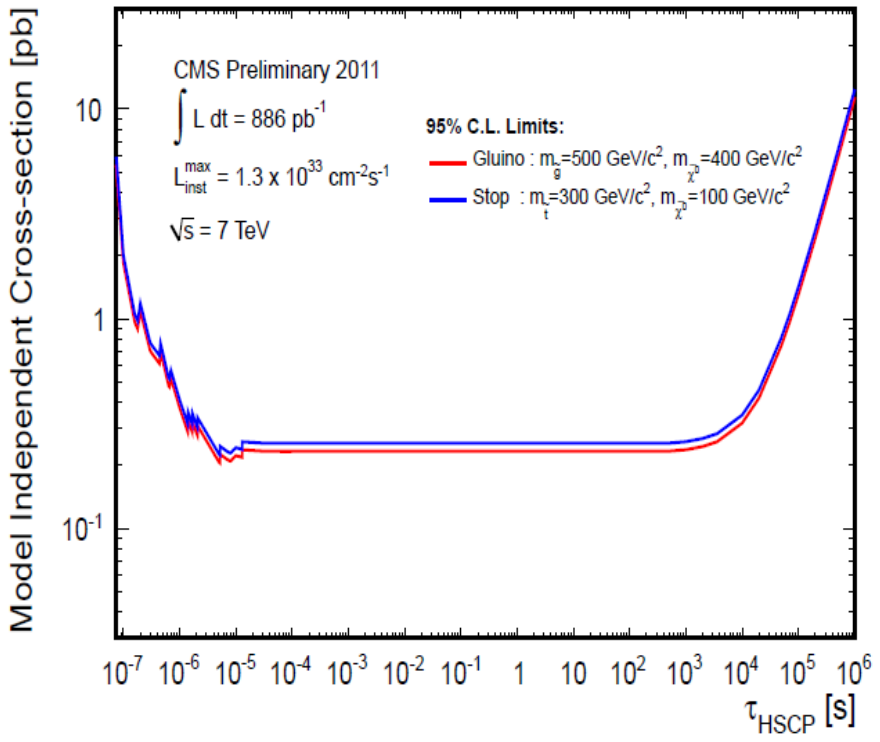
Time Profile Analysis

- For τ<0.7 ms, PDF of decay signal as a function of BX is produced
- Background PDF is flat

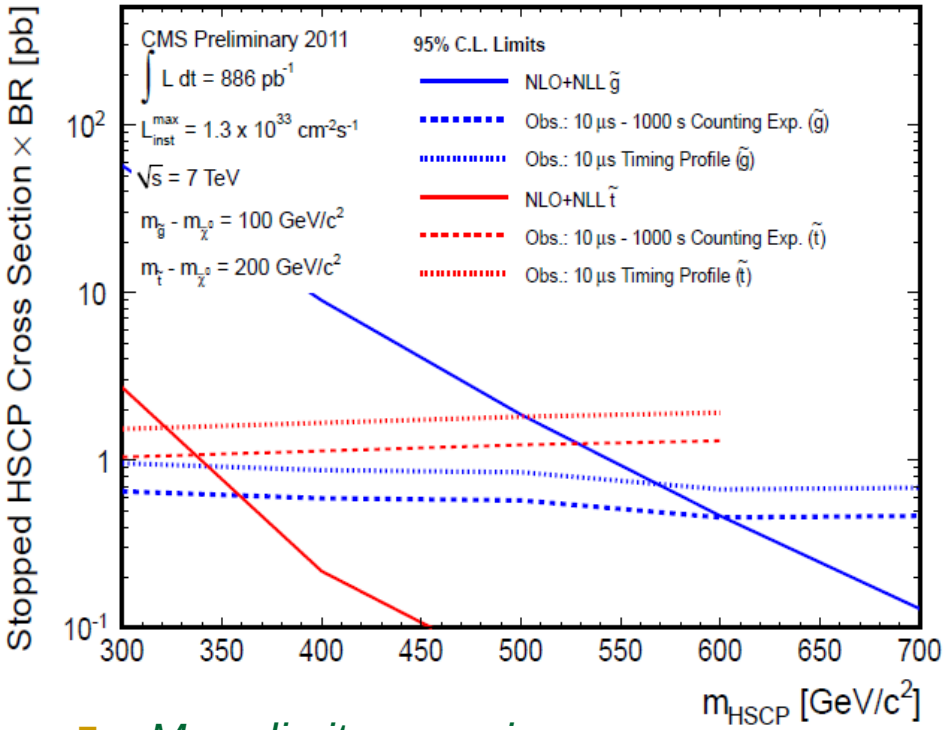


Signal PDF distribution for one Filling scheme, assuming τ=1μs

Stopped HSCP: Lifetime and Mass Limits



95% confidence level upper limit for cross section (x HSCP stopping probability) vs τ



- *Mass limit, assuming:*
  - Cloud model of R-hadron interactions
  - $m_{\tilde{g}} - M_{\tilde{\chi}_1^0} > 100\ \mathrm{GeV}/c^2$
  - $m_{\tilde{t}} - M_{\tilde{\chi}_1^0} > 200\ \mathrm{GeV}/c^2$
- ***Excludes gluinos < 601 GeV/c², stops < 337 GeV/c²***

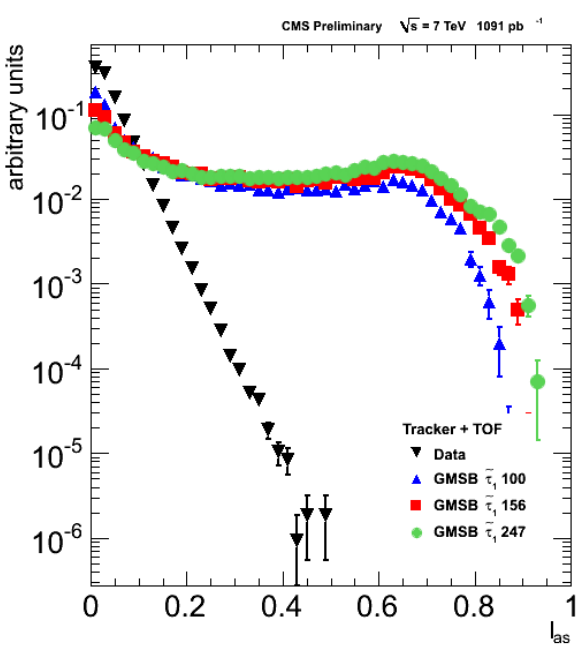
CMS PAS EXO-11-020

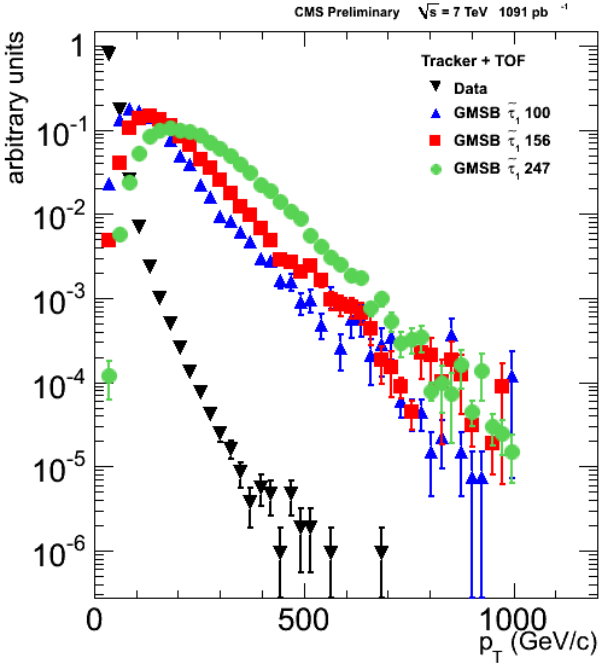
Summary

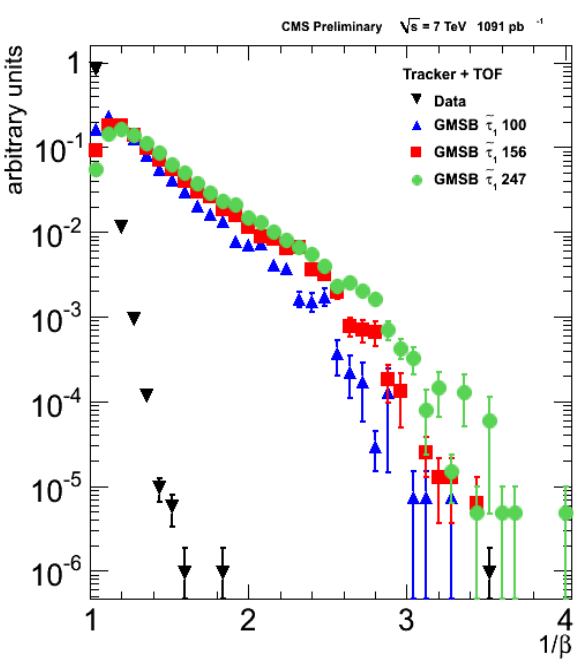
- Search for heavy stable charged particles performed with ~ 1 fb^{-1} of 2011 CMS data
- No evidence for HSCPs seen
- New upper limits set for both direct and stopped HSCP searches

Backup Slides

Backup: Distributions for direct tracker+muon HSCPs







Backup: Direct HSCP Systematics

Source of Systematic Error	Relative Uncertainty (%)
Signal efficiency	
Trigger efficiency	5
Muon reconstruction efficiency	5
Track reconstruction efficiency	< 2
Track momentum scale	< 5
Ionization energy loss scale (I_{as})	[5, 10]
Ionization energy loss scale (I_h)	< 1
Total uncertainty on signal acceptance	[10, 15]
Expected background	10
Integrated luminosity	6

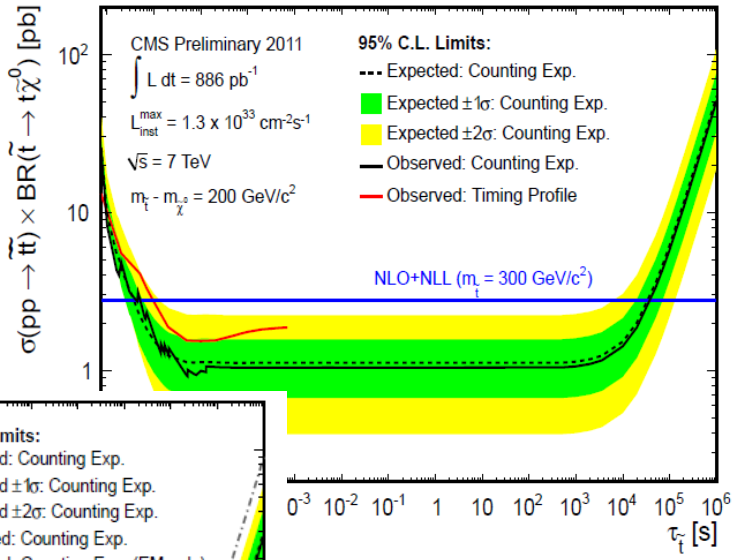
- [5]: *JHEP* **03** (2011) 024, arXiv:1101.1645
- [10]: Phys. Lett **B76** (1978) 575.
- [15]: *JHEP* **05** (2006) 026, arXiv:hep-ph/0603175

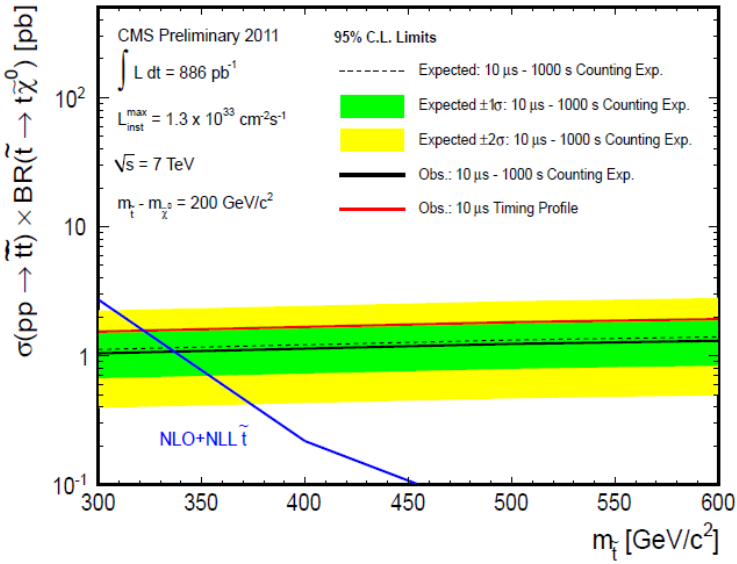
Backup: Stopped HSCP Uncertainties

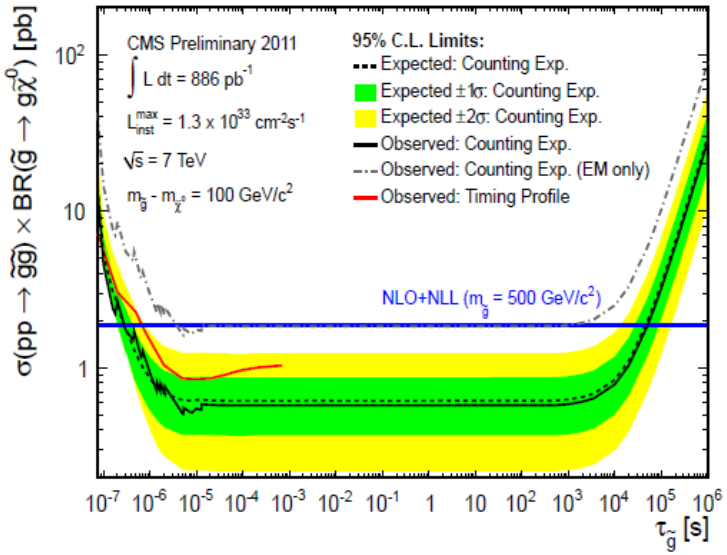
Source	Uncertainty
Background statistics	40%
Jet Energy Scale	7%
Luminosity	6%
Trigger Efficiency	-
Reconstruction Efficiency	-
Energy Loss Models	See following slide

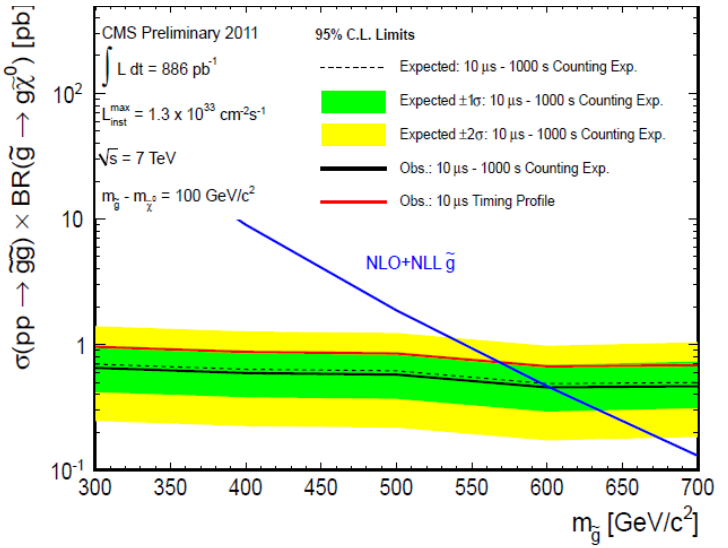
Backup: Stopped HSCP Limits

- Cloud model
- 100% BR to neutralino
- M(gluino)-M(neutralino)=100 GeV/c^2
- M(stop)-M(neutralino)=200 GeV/c^2

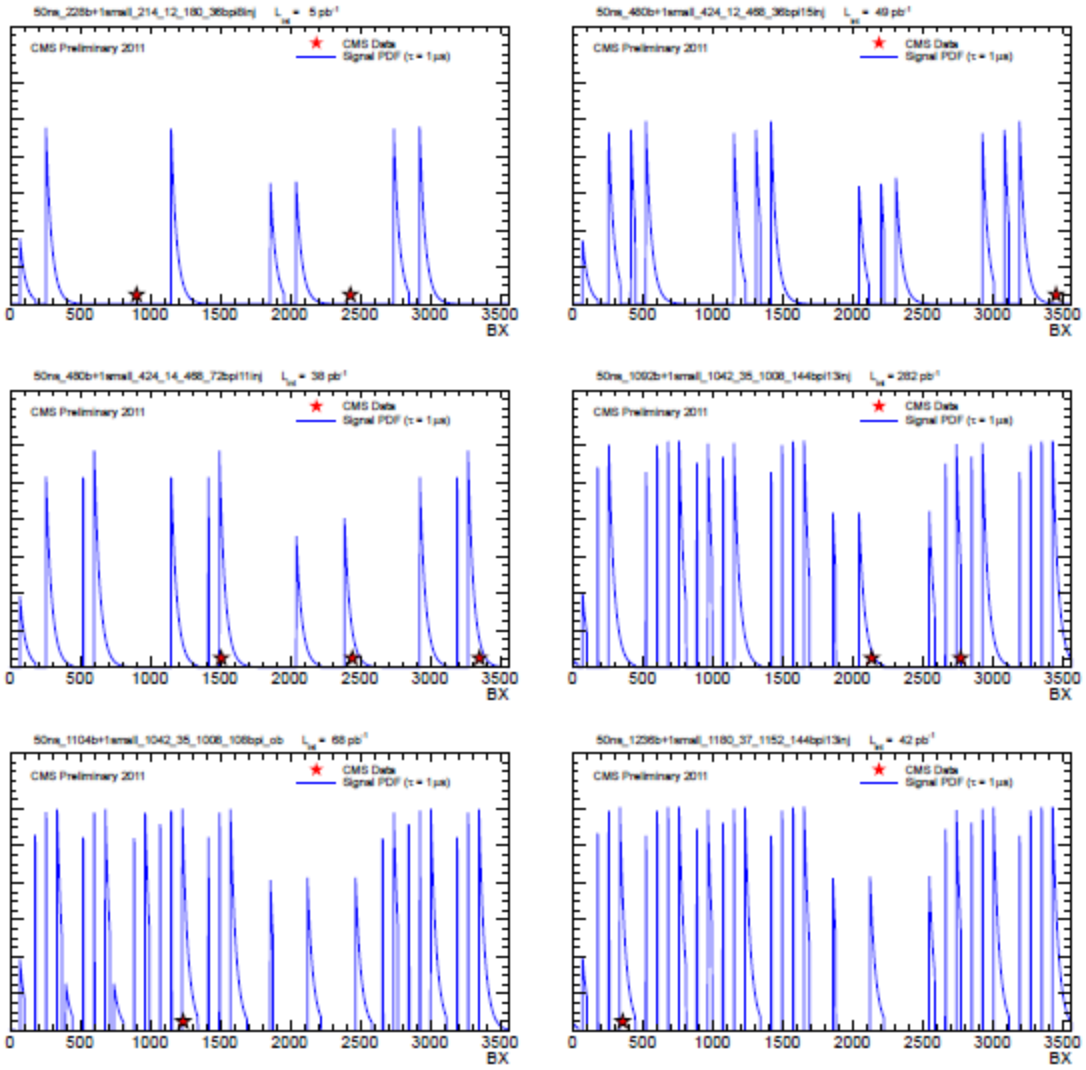




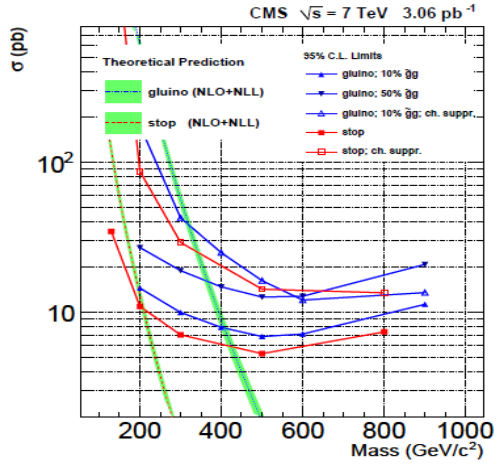




Background: Stopped HSCP Time Profiles for Various Fill Schemes



Background: Previously Published Limits

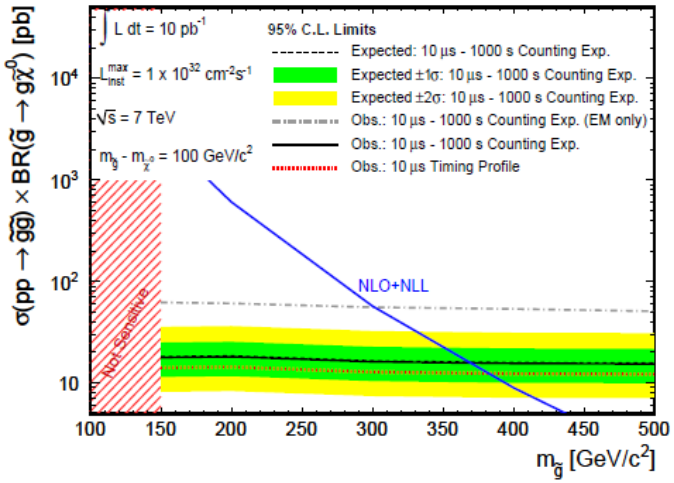


CMS 2010 direct, stopped searches

Gluino exclusion: m<398, 370 GeV/c²

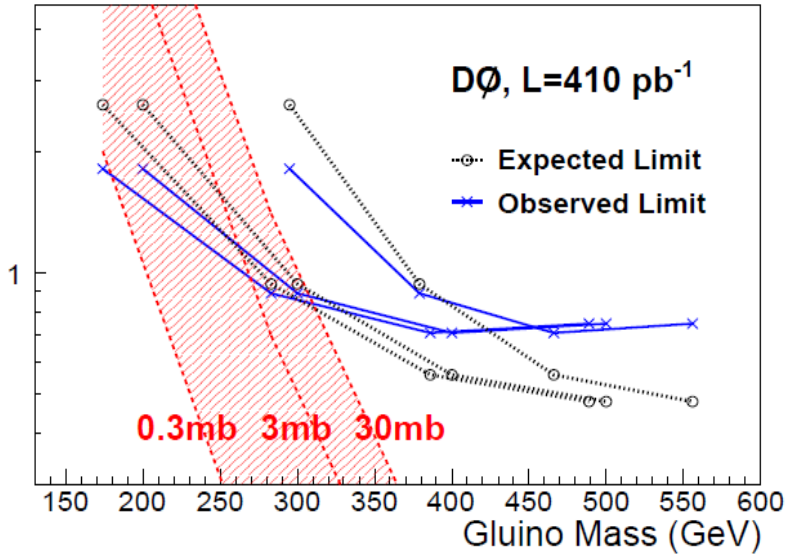
arXiv:1101.1645

arXiv:1011.5861



D0 gluino exclusion: m<270 GeV/c² (50 GeV/c² neutralino)

arXiv:0705.0306



ATLAS direct search gluino exclusion: m<562-586 GeV/c²

arXiv:1103.1984 (also arXiv:1106.4495)